

1. Introduction

Apple orchard design and management have undergone significant changes in recent decades and continued innovation and experimentation is augmenting the large number of combinations of tree density, rootstock, cultivar, pruning and training that make up the orchard design puzzle. The trend in global apple production is towards smaller trees in High Density Plantings (HDP) and is a consequence of the desire to improve orchard productivity and fruit production efficiency and, ultimately, profit.

1.1 National Background

The Australian apple and pear industry comprises around 2100 growers with an average orchard size of 34 hectares. Major apple producing areas are located in most states of Australia. Of the total 1997/98 apple crop of 308 856 tonnes, 30 per cent was produced in Victoria, 25 per cent in New South Wales, 15 per cent in Tasmania, 11 per cent in Western Australia, ten per cent in Queensland and the remainder in South Australia (AAPGA, 1999).

Australian apple orchardists are increasingly replanting orchards with new apple varieties. Traditional apple varieties 'Red Delicious' and 'Granny Smith' still dominate in total apple production. However, tree numbers are declining in favour of new varieties such as 'Fuji', 'Gala', 'Lady Williams', and 'Pink Lady' (Table 1.1). This decline is more evident for Red Delicious when tree numbers aged five years and under are compared. Between 1992/93 and 1997/97 there was a 40 per cent decrease in plantings of new trees (under one year old) and a 57 per cent decrease in the number of trees in the one-to five-year age group (Table 1.1).

Table 1.1 Comparison of apple tree numbers by variety, between 1992/93 and 1997/98

Variety	Apple Tree Numbers ('000)							
	<1 year		1-5 years		>5 years		Total	
	92/93	97/98	92/93	97/98	92/93	97/98	92/93	97/98
Red Delicious	61	34	890	382	1875	2490	2827	2906
Granny Smith	26	44	163	166	1060	960	1250	1170
Fuji	53	77	372	430	45	394	469	901
Gala	65	145	238	726	25	340	328	1211
Lady Williams	5	5	98	22	132	223	234	250
Pink Lady	85	97	152	809	7	254	244	1160
Sundowner	13	113	39	146	4	52	56	311

Source: AAPGA (1995; 1999)

Only a sample of the new varieties being planted in Australian apple orchards is listed in Table 1.1. Among the new varieties, Pink Lady and Gala numbers have shown the largest increase. Pink Lady numbers are particularly large in the one-to five-year age group, where tree numbers were 809 thousand in 1997/98 compared to 152 thousand in 1992/93. New plantings of Gala trees were 145 thousand in 1997/98 compared to 65 thousand in 1992/93.

A portion of domestically produced apples is exported each year although Australia's status as an apple exporter has fluctuated dramatically in recent decades. Prior to its entry into the European Union, around 100 kilotonnes (kt) were exported to the United Kingdom (22 per cent of production). However, since that time, exports reached a low of 16 kt during 1984 (AAPGA, 1995). Plantings of new apple varieties have allowed Australia to become more competitive in non-traditional export markets. In recent years South East Asian nations have accounted for a large portion of Australian apple exports and this market continues to expand.

In addition to planting new apple varieties to enhance export competitiveness, the adoption of HDP technology has aided competitiveness through greatly improved production efficiencies.

1.2 Trends in Orchard Design

The increased planting densities in Australian apple orchards mirrors a trend in Europe that started over four decades ago. Apple orchards in Australia have traditionally consisted of large trees planted at low densities (280 trees per hectare) that took six to nine years to reach bearing age, reached full production at ten years of age and continued production beyond 50 years. Most Australian orchards are now planted at densities ranging from 800 to 1250 trees per hectare (Middleton, 1997). HDP systems are favoured because trees begin bearing at two to four years and, shortly afterwards, they reach full production which may be maintained for many years with appropriate tree management.

Orchards in Europe in general, and the Netherlands in particular, were the earliest to undertake intensification of planting using 'dwarfing' rootstocks. This was an attempt to counter low profitability of apple production and rising land prices. It was expected that 95 per cent of orchards in the Netherlands would be planted at densities greater than 1600 trees per hectare by 1995 (Cahn and Goedegebure, 1992).

The breeding and widespread use of dwarfing rootstocks has allowed the trend towards HDP to occur – trees are planted closely together and tree size at maturity is significantly reduced. Indeed, such a range of dwarfing rootstocks exists that apple trees can be grown to achieve any size or degree of dwarfness at maturity. Despite the already large range of existing apple rootstocks to choose from, there is continued breeding of new rootstocks to improve pest and disease resistance, anchorage, compatibility, fruit size and increased yield efficiency.

As apple orchard densities increased, new ways of pruning and training trees necessarily evolved. The link between adequate light penetration into an apple tree canopy and good fruit quantity and quality has long been recognised and, hence, is an important principle in the various pruning and training strategies that were developed for HDP systems. The two basic approaches to training involve either allowing the apple trees to grow to their natural form, or restricting the tree to geometric forms. Various levels of horticultural skill are required to appropriately manage these systems.

1.3 Economics of Orchard Design

Economic principles are important factors in orchard system design. The choice of tree density, variety, rootstock, training and pruning strategy all directly affect the profitability of the orchard operation because they influence the amount of fruit produced, quality of fruit and production costs. Among the most costly aspects of orchard production are establishment and labour costs.

Establishment costs get progressively higher as tree density increases because of the increased number of trees purchased, tree support structures that may be required for supporting the dwarfing rootstocks and if trellising structures are used. However, while HDP do have high establishment costs, the small size of trees reduces annual management costs per tree and revenue accrues more quickly due to earlier production. Labour costs for pruning, training, and thinning vary for each system, often depending on whether tree size means ladders are used.

Maintaining tree health by ensuring adequate moisture, nutrients and pest control represent additional costs of running an orchard. Maintaining tree health is necessary if profits from fruit quantity and quality decisions are to be maximised.

In making the decision about which variety to plant on a particular rootstock, a large number of apple varieties are available to the orchardist. Considered in the decision are

harvest date, pollination requirements and market prices for the apple produced. Since prices are prone to variation and the availability of harvest labour is often limited, commercial orchardists commonly grow a mix of varieties. The decision about varietal mix is further complicated because new apple varieties are continually being developed in major apple-producing countries in an attempt to gain a competitive edge. The consumer acceptability of new varieties and therefore prices may not be well known at time of planting.

Once an orchard is planted reversal of the tree choice or density decision is costly to undertake, although HDP systems allow for a more rapid changeover time than that afforded by traditional systems. Once the initial planting choice is made, and the orchard reaches full production, growers are faced with an additional decision: choosing whether or not to replace the orchard. This decision is made in the context of orchard profitability. While all apple trees have potentially prolonged productive life times, HDP systems have the advantage of possible earlier replacement. In these systems, replacement commonly happens more often because trees reach maximum production earlier than their larger counterparts. Establishment costs are quickly repaid and high levels of profitability are reached soon after establishment. If new opportunities for increasing long-term profitability arise through the adoption of a new variety, rootstock or training system, it is likely that trees grown in HDP will be replaced sooner than the same trees grown in traditional plantings.

1.4 Modelling Orchard Design and Profitability

Issues that confront the commercial orchardist, such as system design and annual management practices, are investigated in this research using a dynamic simulation model. The model has economic and biophysical components. The economic model describes the costs and revenues associated with orchard systems from planting to maturity and the biophysical component describes the vegetative and reproductive physiology of an apple tree, factors affecting the quantity of apples produced, and the interrelationships between these factors. These two model components are collectively described as a bioeconomic model.

The model captures management decisions that affect fruit production and annual and long-term growth of a tree. The bioeconomic model may be used to simulate fruit production stemming from a range of orchard systems by varying particular model parameter values. Such parameters include those that reflect tree form and how light is intercepted by the particular form. Introducing establishment costs, annual costs of labour,

nutrients, chemicals and irrigation allows system profitability to be simulated in a realistic way. An important use of the model is therefore, to seek out the system design and management practices that maximise profitability.

1.5 Thesis Structure

The concept of a bioeconomic model is discussed in Chapter 2, along with a brief account of previous attempts at modelling in deciduous fruit-tree research. Models discussed are mainly those concerned with stone and pome fruit. The biophysical component of the bioeconomic model used in this study is then developed in Chapter 3.

Modelling orchard design issues about cultivar choice, density, rootstock selection, pruning and training and the ongoing management issue of thinning are discussed in Chapter 4. While choices concerning orchard design are made prior to planting, thinning, in response to the biennial bearing of an apple tree, is a decision made during each year of fruiting and is assumed to be the only way that profitability of a system may be varied once planting has occurred. Tree replacement is an important issue for commercial orchardists and while it is briefly discussed in this chapter, is not considered further.

While a large number of orchard systems is possible, only a sub-set of these is considered in this study and these are outlined in Chapter 5. These include a range of cultivars planted in a traditional, wide spaced planting trained to a vase shape, through to cultivars planted on the dwarfing M.9 rootstock at 4400 trees per hectare using a trellis structure. Price of inputs and outputs assumed to apply in each system are discussed in this chapter.

The biophysical model is analysed in detail in Chapter 6. This chapter gives simulation results for annual tree growth and cumulative fruit yield for various systems. Simulated fruit yield is compared to several sets of experimental data from similar systems. An important part of this chapter is sensitivity analysis undertaken on certain parameters whose values were uncertain. Sensitivity analysis is undertaken in order to understand how sensitive the results from the model would be to small errors.

In Chapter 7 the biophysical model is incorporated into the economic model with a view to maximising net present value (NPV) of a given system over a 15-year time horizon by selecting optimal thinning levels. The simulation provides the level of thinning in each year that maximises NPV given the inherent tendency towards biennial bearing from the biophysical model. This innovation represents a significant contribution to understanding of the orchard problem. Thinning, a crucial part of annual orchard management has

largely been ignored by both economists and horticulturists in their attempts to analyse long-term fruit production. An important part of the optimisation process is the solution technique used and several possible alternatives are discussed in this chapter.

The NPV of 25 different systems is simulated in Chapter 8. Optimal thinning strategies, cumulative fruit yields and profitability are given for each system, and comparisons made.

A final model application, the simulation of a two-spotted mite outbreak, is undertaken in Chapter 9. The effect on NPV from using two alternative methods of control, chemicals and predators, are compared. The use of a predator-prey model gives an insight into orchard profitability when reliance on predators for mite control is adopted. This application is undertaken in the context of the increasing difficulty in controlling mites using chemicals due to widespread or impending resistance.

Finally, conclusions are offered in Chapter 10. It is hoped that the inter-temporal bioeconomic model developed and applied in this study will give greater insight into orchard management strategies, especially in the context of profit maximisation. The model allows simulation of a wide range of orchard systems for a range of locations although not all are covered in this study. In addition, the model provides an insight into how thinning strategies and pest control may influence long-term profitability given the inherent biennial bearing nature of the apple tree.

The author knows of no other study that simulates orchard production from planting to maturity using this type of detailed bioeconomic approach.

2. Modelling in Deciduous Fruit Tree Research

Orchard systems are complex. Managers of deciduous perennial fruit crops must consider both biological and economic relationships in determining preferred orchard design and life-time orchard management strategies. Decisions about variety, tree size and varietal mix made at planting determine potential yield over the lifetime of the orchard. These decisions also influence costs and profit per hectare and, by necessity, are made in the context of unknown future prices of inputs and outputs. Once trees are bearing fruit, the decision concerning the amount of fruit to leave on the tree until harvest remains one of the few ways that the value of the annual orchard yield may be influenced.

2.1 The Role of Modelling

A simulation model representing the orchard system is a particularly useful means of evaluating the effects on yield and profitability of alternative orchard systems and other decisions under the direct control of the orchardist. Given the importance of biological and economic components in orchard profitability, both elements should feature in the model if the orchard system is to be adequately described and simulations meaningful. One objective in this thesis is to develop a dynamic optimising model of an apple orchard that is able to simulate alternative management decisions, including optimal thinning and pest control choices. Lack of data on yields of many important apple varieties overtime means it is necessary to adopt a bioeconomic approach.

A bioeconomic model consists of a biophysical model, which describes a production system, and an economic model that relates the production system to market prices and resource constraints. The economic model provides the link between the market and the production system and controls the operation of the biophysical model by controlling inputs and obtains feedback from the biophysical model as outputs (Cacho, 1997). If the economic model is designed as an iterative optimisation model, the input-output cycle might occur thousands of times, with inputs being adjusted in response to outputs until an optimal solution is obtained (Cacho, 1997).

Once developed, an important use of bioeconomic models is simulation. Simulation models of agricultural systems have grown in popularity in recent decades due to their usefulness in tackling the inherent dynamic and/or stochastic nature of agricultural problems and due to increased computer capacity (Oriade and Dillon, 1997). Simulation

may substitute for large-scale physical experimentation, which could otherwise take decades, especially in the case of perennial crops.

A bioeconomic model can be a systems model that includes economic components or a multiequation model with a single equation representing the biological system (Cacho, 1997). The biological simulation models that underlie bioeconomic models may vary considerably in their complexity and depend critically on the purpose for which they are constructed. The biological simulation models developed by biologists and agricultural scientists are often too detailed to be used in optimising economic models designed by economists. Conversely, simulation models developed by economists tend to be too simple by biologist's standards with models consisting of linear or simple non-linear functions to allow for solution of optimisation problems (Cacho, 1997). Bioeconomic models may be developed using either non-optimising (positive) or optimising (normative) frameworks. Optimising models provide the decision maker with courses of action that will lead to the optimisation of a particular criterion, while non-optimising, positive models, indicate outcomes resulting from alternative decisions.

2.2 Previous Studies

Despite the development of a large number of bioeconomic models for use in management of annual crops (see Penning de Vries and van Laar, 1982; Oriade and Dillon, 1997), models are not available for perennial tree-crop research of the type conducted here. Instead, a large number of biophysical models and biological models that describe particular aspects of individual apple-tree growth and fruit production have been developed and only a few have been used in conjunction with an economic modelling framework. While modelling of perennial crops undertaken by economists include yield estimates, these are rarely the output of detailed simulation models. It is most common for yield functions to be estimated from experimental data or survey information. These models and those developed by biologists which contain simple economic relationships are all loosely described as bioeconomic models in this analysis.

Bioeconomic models developed by economists to analyse issues in perennial-crop research commonly use both non-optimising and optimising frameworks. Maximising the discounted value of profits (NPV) subject to aspects of orchard operation, including optimal replacement of trees and optimal mix of tree varieties, are typical objectives of these models. Non-optimising models tend to assess profit outcomes resulting from a narrowly defined set of alternative management strategies.

Table 2.1: A chronological sample of published tree crop models

Author(s)	Tree type	Biological model	Optimisation/analysis techniques	Decision variables	Objectives
Willis and Hanlon (1976)	apple	survey-generated yield information	dynamic linear programming	variety, capital borrowing	optimal tree mix, maximise PV net returns
Winter (1976, 1986)	apple, pear	mechanistic, (FRUPRO)	simulation	planting density, variety, rootstock, orchard size	orchard system profitability comparisons
Graham et al. (1977)	apple, cherry, pear	survey-generated yield information	Single/multiple period linear programming	orchard system, variety and type, timing of replacement	Profitability, optimise labour, cash borrowing requirements, renewal strategy
Childs et al. (1983)	apple	empirical yield estimation	simulation/dynamic programming	replacement policy	maximise profit
Haley et al. (1990)	apple	mechanistic	inference procedures, simulation	pest numbers	assess benefits of pest control, decision support
Johnson & Rasmussen (1990)	peach	empirical	simulation	fruit load	maximise profit
Thiele & Zhang (1992)	apple	empirical	dynamic simulation model	fruit load	explore revenue per hectare, decision support
Groot (1996)	apple, pear	empirical	simulation	crop protection system	explore cost of pesticide reduction, decision support
Cahn et al. (1997)	apple	empirical	simulation	planting density, year of first harvest	explore NPV, IRR, decision support
Whitaker & Middleton (1999)	apple	yield estimation	cost-benefit analysis, simulation	orchard system, erection of hail net	Profitability of hail netting

Biologists and horticulturists also use optimising and non-optimising bioeconomic models of perennial-orchard operation. These models typically use simple economic models attached to well developed biophysical models to analyse specific aspects of fruit production and orchard management, normally for a single growing season. Aspects of management include alternative thinning strategies and their effects on orchard returns (Thiele and Zhang, 1992; Johnson and Rasmussen, 1990).

Table 2.1 presents a chronological review of bioeconomic models developed for analysis of deciduous perennial tree crops. The list is not exhaustive; rather, it represents trends in perennial crop research by both horticulturists and economists. While the models used are described as bioeconomic in scope, it is acknowledged that many bioeconomic modellers would preclude several of these models from this category because they are without some well defined economic and/or biological elements.

In general, it appears that the apple is the most popular deciduous fruit tree for modelling purposes. Researchers have employed simple empirical biophysical models to describe fruit orchards and specific aspects of fruit production, although detailed bioeconomic models of orchard management are largely missing from the research. A large number of simulation models are developed as decision support tools for growers. While simulation features prominently as the chosen analysis technique, dynamic programming, mathematical programming and cost-benefit analysis techniques are also used. Orchard replacement policies and fruit variety mix are the most common decision variables. Other decision variables include planting density, fruit load, capital borrowings, rootstock, pest number and use of hail netting. Profit maximisation and/or profit simulation is the most common objective of the modelling work. A brief description of the papers follows.

Willis and Hanlon (1976) and Graham et al. (1977) are examples of research using linear programming to analyse orchard profitability. Neither paper employs a detailed biophysical model. Rather, data on apple-tree yields gained from survey information are used to generate yield coefficients. Willis and Hanlon (1976) develop an analytical framework for achieving, over time, an optimal mix of apple varieties for a case-study farm. Their framework considers alternative goals such as minimum acceptable family living standards and maximum acceptable risk using a lexicographic approach. The authors maximise the following objective function subject to a series of storage, labour, market and land constraints:

$$R = \sum_i \sum_j \sum_t c_{ij}^t x_{ij}^t \quad (i=1,\dots,I; j=1,2; t=1,\dots,T) \quad (2.1)$$

where R is the present value of the expected stream of net returns resulting from the x_{ij}^t planting acreage decisions, c_{ij}^t is the stream of net income per acre expected from planting variety i in period t , to be harvested by method j and to be removed in period $t + \Delta$, where Δ is the useful life of variety i . The two methods of harvesting are using either full-time labour ($j=1$) or seasonally hired labour ($j=2$).

The lexicographic model is applied to a model farm consisting of 80 acres of apples of various ages and varieties with a view to finding an optimal mix of tree varieties. It was assumed that trees are removed after age 25. The optimal solution to the basic model was compared to a situation where the initial mix of varieties was continued. The objective function was 25 per cent higher in the optimal solution than that from continuation of present practices (Willis and Hanlon, 1976).

Graham et al. (1977) also take a case study approach in determining the optimal mix of fruit trees for a given orchard. Single- and multi-period linear programming models are used to determine optimal renewal strategies and combinations of fruit enterprises (cherry, apple and pear) through comparisons of life-time profitability.

Winter (1976, 1986) develops one of the most detailed bioeconomic models of an apple orchard in the literature. Called FRUPRO, it is used to compare profitability of various apple and pear orchard systems. The biological component of the model is based on a yield-forecast system:

$$Y = TC \cdot FD \cdot \overline{FW} \quad (2.2)$$

where Y is yield, TC is the fruiting capacity of the trees, FD is the density of fruit set and \overline{FW} is the mean fruit weight. All elements of yield are influenced by a series of genetic and ecological parameters that vary by variety and orchard area respectively. The annual development of trees and their yields are calculated for the assumed 30 years of productive life. FRUPRO allows the user to investigate the effects of decision variables, including different planting systems, prices and wages, on endogenous variables including yield, costs, income and profitability. FRUPRO has been used by other researchers to investigate orchard replacement (Buchwald, 1986) and orchard profitability (Gross and Rais, 1986).

Optimal replacement is analysed using a dynamic programming framework in Childs et al. (1983). The empirical biological model consists of a series of yield curves for several

cultivar/rootstock and age combinations. A quadratic function is used to estimate the yield curves from survey data of New York apple orchardists.

The dynamic programming model maximises the net present value of after-tax cash flow from selected replacement strategies. The dynamic programming model is initialised by defining five policies: keep the current orchard; replace with standard trees; replace with semi-dwarf trees; replace with interstem trees (which removes the need for support); and replace with dwarf trees.

Childs et al. (1983) use the Howard approach to dynamic programming, which in turn uses the Policy Iteration method for finding an optimal solution. This method involves solving a set of simultaneous equations rather than working backwards to a final solution as occurs in traditional dynamic programming. The Policy Iteration method is a two-step procedure consisting of a Value Determination routine and a policy improvement routine. The Value Determination routine solves a system of simultaneous equations using a chosen policy (R_1) for the unknown value $V_i(R_1)$:

$$V_i(R_1) = Q_{i,k} + \sum_{j=0}^N P_{i,j}(K_1)V_j(R_1) \quad (i=0, 1, \dots, m) \quad (2.3)$$

where i is the current state of the system, j is the new state of the system in the next observed time period, R is the policy followed, $Q_{i,k}$ is the expected return (after-tax cash flow) in state i obtained from following policy R , $P_{i,j}$ is the probability that the system is now in state i and that decision K is made (transitional probability) and K is the decision made in state i when following policy R .

The Policy Improvement routine then uses the vector of solutions from (2.3) to determine a better policy R_2 by minimising the cost or maximising the contribution in each state. This is done for each state i by finding K_2 that maximises:

$$Q_i K_2 + \sum_{j=0}^N P_{i,j}(K_2)V_j(R_1) \quad (2.4)$$

The minimum cost or maximum contribution found becomes the new policy. Equation (2.3) and objective function (2.4) are repeated until the iterations of both converge to identical policies for successive iterations, the resulting policy is the optimal one (Childs et al., 1983). Using average price, cost, production and yield data for New York State, the model outcome was to immediately replace the current orchard with interstem plantings, if it consisted of either standard trees of all ages or semi-dwarf trees under nine years of

age. The interstem systems and other dwarf systems were kept until age 30, the assumed final year of economic life. Replacement with interstem plantings would then occur as the optimal policy. In their modelling work, Childs et al. (1983) were able to analyse optimal timing of orchard replacement, an issue that previous authors had been unable to tackle.

Studies by Haley et al. (1990) and Groot (1996) examine pest control strategies in apple and pear orchards using simulation models. Haley et al. (1990), a team consisting of a researcher, a pest manager and a computer scientist, develop a decision-support model that assesses the benefits of pest control in apple orchards. The model identifies the potential success of biological control for the pest in question, benefits and costs of pest control and possible side effects of using a particular pesticide. Benefits of pest control are determined by assessing crop value, likely damage inflicted by the pest and efficacy of the pesticide used. The decision support model developed by Groot (1996) uses an empirical model to calculate the economic and ecological consequences for a fruit farm of using different crop protection strategies. The context of the study is the legislated reduction in the use of farm chemicals in Dutch agriculture by 44 per cent in the year 2000 compared to the 1984-88 levels.

Johnson and Rasmussen (1990) and Thiele and Zhang (1992) are also interested in a single aspect of fruit production – fruit size. Given that large-sized fruit are more valuable than small fruit, it is common practice for orchardists to remove a number of fruit from the tree in order to improve average fruit size of those that remain. Johnson and Rasmussen (1990) investigate the optimal economic fruit load for peach trees. The relationship between average peach size and fruit number per tree is estimated using linear regression, then individual fruit weights are fitted to a normal distribution around the mean weight. Prices for various fruit sizes and variable costs of running a peach orchard make up the economic model and optimal fruit load is defined as that level where maximum net revenue occurs. The authors only consider one growing season and provide no guidance on lifetime thinning strategies that might be useful to apple thinning.

Thiele and Zhang (1992) develop a model that is also aimed at measuring the relationship between thinning and crop value. Their model is developed as a decision support tool for apple orchardists and requires growers to enter their own biological data by counting flower and fruit numbers during the season, and to enter labour, material and machinery usage for their operation. The model provides for four alternative management strategies: (i) planning from the flowering period; (ii) planning from the fruit number, before thinning but after fruit set; (iii) planning after thinning when final fruit number is known; and (iv) assessing financial strategies by testing various price levels. Each strategy requires different information from the grower. The empirical biophysical model is used

to simulate gross margins for alternative thinning strategies based on the timing and severity of thinning in a given year. While the authors acknowledge the dynamic and perennial nature of the apple tree and the issue of interaction between one year and the next, a correction factor for biennial influence was not included in the model.

The aim of the simulation model developed by Cahn et al. (1997) is decision support. The model predicts the economic outcomes for different planting strategies and includes the age at which apples are left on the tree for the first commercial harvest. The biological model is empirical and uses data from trials and other research to develop relationships between planting strategies, inputs and outputs. The computer model predicts the economic outcomes of one hectare of apples for four decision scenarios.

Whitaker and Middleton (1999) use cost-benefit analysis to determine the profitability of hail netting for various apple varieties in high-density plantings. The authors analyse profitability of hail netting assuming the high-density orchard systems are all replaced after their fifteenth year. Orchard yields with and without hail netting are taken from experimental data and represent the only biological information used by the simulation model.

2.3 Summary

The models described above vary in their capacity to answer the questions posed of them. Most are non-optimising predictive models and few employ detailed mechanistic models of fruit-tree growth that would enable the simulation of any orchard system from planting to maturity.

The biophysical model developed in this thesis is specified at the level of the tree and interacts with the economic model at the level of the orchard. Daily and seasonal growth cycles are important in understanding orchard productivity hence a dynamic biophysical model is developed that uses differential equations to describe changes in state variables through time. The dynamic biophysical model is integrated with a dynamic optimisation economic model that uses simulations to solve non-linear programming problems. The biophysical model is described in detail in the following chapter.

3. Biophysical Model

A model of the growth cycle and fruiting habits of an individual apple tree is presented in this chapter. The model simulates the basic physiological processes of photosynthesis, respiration and dry-matter partitioning and takes into account the vegetative and reproductive physiology of apple trees. The most important factors affecting the quantity and quality of apples produced, and interrelationships between these factors are also considered. Leaf, root, stem and wood (branches and trunk) and fruit growth are simulated through a series of submodels which allow incorporation of alternative apple cultivars and canopy architectures. Processes that are unique to deciduous perennials, including development of winter hardiness, physiological rest, and accumulation of stored materials to fuel renewed growth following rest are also accounted for.

The model of individual apple tree growth is later modified to represent growth and fruit production of an orchard of apple trees, including the effect of orchard design and management practices on the quantity and quality of apples produced. The model is specified at a level of aggregation which is appropriate for incorporation into an optimising economic model of apple orchard management.

3.1 The Apple Tree

A commercial apple tree (*Malus*) is composed of a piece of a particular 'cultivar' (*cultivated variety*) also called a scion, that is grafted or budded onto a rootstock. This vegetative propagation allows the cultivar to maintain all the characteristics of the original tree. A large number of apple rootstocks and scion varieties have been available to apple growers for several decades and each combination has its own implications for orchard management.

A specific rootstock is normally chosen for the tree size it will produce. Historically, the most commonly available rootstocks produced trees of variable size and performance. In modern orchards, where size of the apple tree plays a central role in orchard management, and where tree uniformity, precocity and crop efficiency are crucial, most trees are planted on one or more of clonal rootstocks developed after 1900. The large number of rootstocks now available means that trees can be grown to achieve almost any size or degree of 'dwarfness'.

The scion section of the apple tree determines fruit variety and fruit features such as size, shape, colour, flavour, firmness, ripening season and pest and disease resistance. The rate of scion growth (vigour) depends on intrinsic vigour of the scion and vigour potential of the chosen rootstock. Growth is also affected by factors such as climate (light, temperature and rainfall), soil characteristics, management factors (pruning, training and weed control) and status of the tree (health and crop load) (Webster, 1995).

The age at which an apple tree first bears fruit (its precocity) will vary according to the rootstock/scion combination. The reproductive process commences in the growing season prior to dormancy with formation of fruit buds; it ends with harvest in the following season.

3.2 Conceptual Model

Apple tree growth during a growing season and over a lifetime is described using a carbon-balance model. Seasonal growth patterns that are peculiar to deciduous woody perennials such as apple trees, form an integral part of the model. The conceptual model (Figure 3.1) is described in the following subsections.

3.2.1 Overview of the model

The critical environmental variables in the model are daylength, temperature and light – all three affect the growth potential of the tree. Light (radiation) and daylength affect canopy photosynthesis, while temperature affects both photosynthesis and respiration. Light interception is critical to the amount of photosynthesis undertaken by an apple tree and level of interception is determined by shape of the tree which is, in turn, influenced by chosen pruning and training techniques and tree age. Net photosynthesis describes the amount of carbon available for tree growth after accounting for carbon lost during leaf respiration and gained through photosynthesis.

Carbon represents the energy used for growth by each tree component: roots; wood; fruit; and leaves. Respiration of roots, wood, leaves and fruit results in energy losses. The 'fruit load' on the tree is the major determinant of how energy is divided between each tree component and is influenced through a management practice known as thinning.

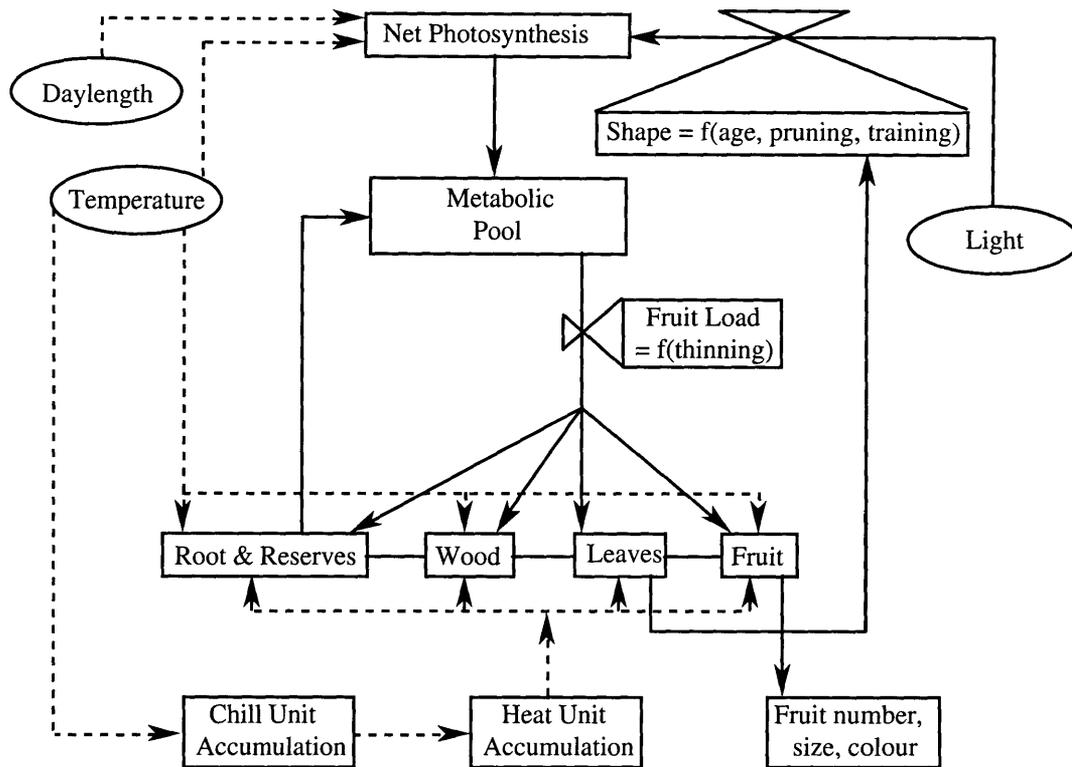


Figure 3.1: Conceptual model

Fruit load also influences size of individual fruits and has an impact on future fruit production through its effect on amount of root, wood and leaf that grows in the current and following seasons. Fruit is harvested annually and its quantity and quality is taken into account by the model.

3.2.2 Seasonal effects

Apple trees follow temperature-driven patterns of growth and non-growth over a 12-month period. A simplified 'calendar' of apple tree growth as it relates to temperature is depicted in Figure 3.2. Apple tree growth is represented as the presence or absence of leaf and fruit on the apple tree.

During late autumn, apple trees enter a dormant period where vegetative and reproductive buds require a period of chilling temperatures if bloom, growth and development are to occur in the spring. Dormancy is broken once the chilling requirement of the particular apple cultivar has been satisfied. In Figure 3.2 this occurs during mid-July. Growth, however, does not automatically resume at this point, rather, it occurs following higher daily temperatures that result in accumulation of a certain number of heat units. Leaf growth and fruit growth (bloom) are depicted as occurring during early and mid September, respectively, in Figure 3.2.

Fruit growth continues through spring and summer. Depending on the cultivar, maturity and harvest of the fruit occur sometime between February and late April. In Figure 3.2 fruit harvest occurs during mid-February. Upon the onset of cooler temperatures, during May in Figure 3.2, the leaves begin to fall from the tree. Seasonal changes in tree status are introduced into the model through temperature-driven 'triggers'.

The model also allows for accumulation and use of reserves stored in the root system to provide energy for leaf development and growth during early spring. The provision of carbon from the root to the rest of the tree, hereafter referred to as root donation, is also triggered by favourable temperatures in the spring.

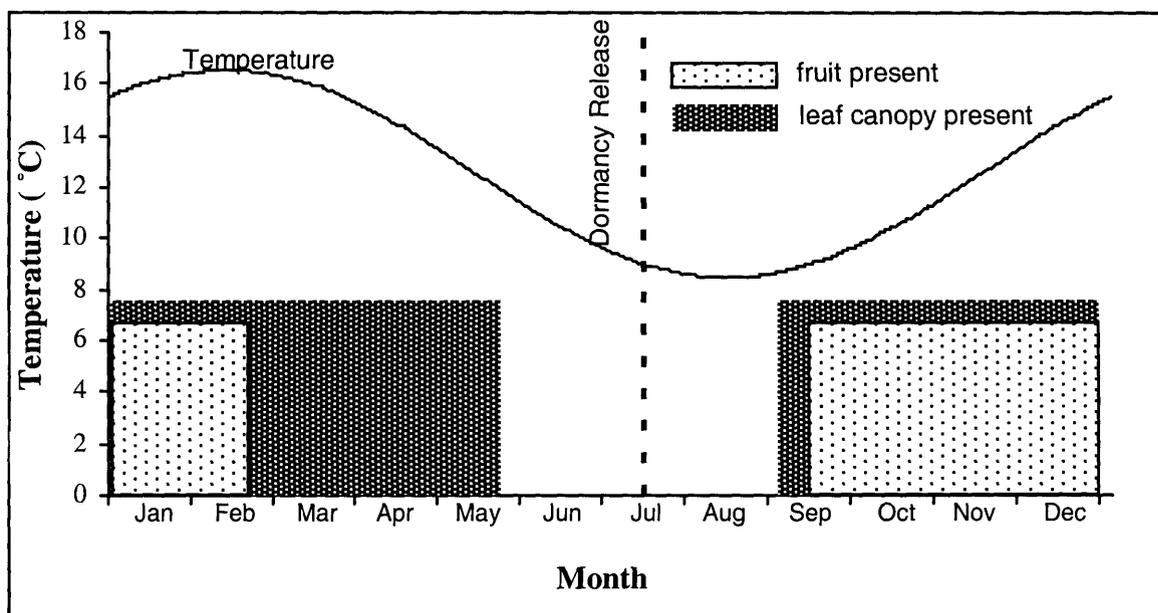


Figure 3.2: Average daily temperature and calendar of apple tree growth for southern hemisphere locations

3.3 Carbon Balance Model

Apple tree growth is described using a carbon-balance model, based on the second law of thermodynamics. The second law states that in any energy transformation process there is always a degradation of energy from an organised to a random form, the latter usually being termed heat energy (Bayliss-Smith, 1982). The mass of living matter can be converted to units of carbon (energy), which can be accounted for and 'followed' through the process of photosynthesis, respiration and growth. Increases in carbon, measured as dry matter, are partitioned among the leaf (L), wood (W), fruit (F), and root (R) to enable growth. The daily gain in mass of each tree component over time is defined as:

$$\frac{dw_j}{dt} = \left[(P_d - R_{d_j})\psi + CHO \right] \rho_j \quad \text{for } j = L, W, F, R \quad (3.1)$$

where w_j represents dry matter mass (grams) of component j , P_d is daily photosynthesis, R_{d_j} is the respiration of each tree component, CHO represents carbohydrate reserves, ρ_j is the proportion of dry matter partitioned to component j , and ψ is a conversion factor between carbon and dry matter (DM). Of the dry matter that results from the photosynthetic process, approximately 30 per cent is lost due to conversion costs (Penning de Vries and Van Laar, 1982) and the remainder is allocated to each plant part. The following subsections describe the model in detail. Parameter values, specific to all apple trees, are presented in Table 3.1.

Table 3.1: Non-system specific parameter values

Parameter	Value	Units	Source	Equation
ψ	0.667	$\text{m}^2 \text{ g DM } (\text{CO}_2)^{-1}$	Sesták et al. (1971)	3.1
K	0.6	$\text{m}^2 \text{ ground } \text{m}^{-2} \text{ leaf}$	Jackson (1978)	3.2
α	14600	$\mu\text{g CO}_2 \text{ Joule}^{-1}$	Proctor et al. (1976)	3.5
P_{max}	0.00075	$\text{g m}^{-2} \text{ s}^{-1}$	Watson et al. (1978)	3.5
α_L	0.5182	$\text{g m}^{-2} \text{ d}^{-1}$	Watson et al. (1978)	3.7
β_L	0.084		Butler and Landsberg (1981)	3.7
α_W	0.000719	$\text{g DM } (\text{g DM})^{-1} \text{ d}^{-1}$	Elfving et al. (1983)	3.7
β_W	0.084		Butler and Landsberg (1981)	3.7
α_R	0.001545	$\text{g DM } (\text{g DM})^{-1} \text{ d}^{-1}$	Elfving et al. (1983)	3.7
β_R	0.084		Butler and Landsberg (1981)	3.7
α_F	0.00411	$\text{g DM } (\text{g DM})^{-1} \text{ d}^{-1}$	Elfving et al. (1983)	3.7
β_F	0.084		Butler and Landsberg (1981)	3.7
h_M	4360	seconds	Charles-Edwards (1982)	3.8
N	28.22	$^\circ\text{latitude}$		3.9
ζ	0.04	a	Hansen (1977)	3.15
χ	0.794	a	McArtney et al. (1996)	3.17
θ_L	0.18	a	Heim et al. (1979)	3.19
λ_L	-0.085	a	Heim et al. (1979)	3.19
τ_L	6.85	$\text{fruit no } (\text{m}^2 \text{ LA})^{-1}$	Heim et al. (1979)	3.19
θ_W	0.41	a	Heim et al. (1979)	3.19
λ_W	-0.30	a	Heim et al. (1979)	3.19
τ_W	6.05	$\text{fruit no } (\text{m}^2 \text{ LA})^{-1}$	Heim et al. (1979)	3.19
θ_F	0	a	Heim et al. (1979)	3.19
λ_F	0.86	a	Heim et al. (1979)	3.19
τ_F	9.6	$\text{fruit no } (\text{m}^2 \text{ LA})^{-1}$	Heim et al. (1979)	3.19
TB	4	$^\circ\text{C}$	Anderson et al. (1986)	3.22
σ	0.15	$\text{g DM } (\text{g FW})^{-1}$	Schechter et al (1993)	3.23
a_0	0.2	CU	Shaltout and Unrath (1983)	3.21
a_1	0.21	CU $(^\circ\text{C})^{-1}$	Shaltout and Unrath (1983)	3.21
a_2	-0.01	CU $(^\circ\text{C})^{-1}$	Shaltout and Unrath (1983)	3.21

a: denotes unitless parameter

3.3.1 Light interception

Light interception and penetration into an apple-tree canopy are key determinants of the level of photosynthesis undertaken by the tree and thus determine dry-matter production and yield. Light interception and distribution are affected by shape and size of the tree, and by amount and arrangement of leaves, fruits and branches within the tree canopy (Palmer, 1980). As the leaf canopy of the tree develops during spring, light interception increases. However, increases in leaf area may sometimes lead to shading so that light penetration into certain parts of the canopy may be inadequate for photosynthesis and fruit production. Tree shape is critical in this respect.

The amount of light reaching any given depth within the canopy depends on the amount of foliage between that point and the irradiated surface, and on total amount of light intercepted by the tree (Jackson, 1980a). Since an *individual* tree may be considered as a continuous canopy, it can be argued that light penetration approximately follows a Beers-Lambert type of relationship which was first modelled by Monsi and Saeki (1953, cited in Thornley and Johnson, 1990) in this context:

$$\frac{I_{LAI_T}}{I_0} = e^{[-K LAI_T]} \quad 0 < K < 1 \quad (3.2)$$

where I_0 and I_{LAI_T} are irradiances above and within the canopy at a particular leaf area index respectively (watts PAR (m^{-2} ground)), where *PAR* denotes photosynthetically active radiation, LAI_T is tree leaf area index (m^2 leaf m^{-2} ground) and K the light extinction coefficient. Equation (3.2) may be used to show the maximum possible leaf area index in the zone receiving more than, say, 30 per cent of full daylight, so that

$$\frac{I_{LAI_T}}{I_0} = 0.3.$$

The light extinction coefficient describes how light is 'extinguished' as it passes through the canopy. Increasing values of K indicate a greater proportion of light is attenuated for a given amount of leaf area. K values for canopies with prostrate leaves are observed to be greater than those canopies where leaves are more erect.

The value of K varies between orchard systems and between cultivars (Faust, 1989). Cain (1973) calculated values of K ranging from 0.43 to 0.77 in apple trees, and Jackson (1978) calculated K values ranging from 0.44 to 0.76, with an average value of 0.6, for different tree arrangements and ages. Jackson's average K value of 0.6 is the widely accepted value

of the extinction coefficient (Jackson and Palmer, 1979; Faust, 1989) and is the chosen value of K in this study.

The tree leaf-area index is the ratio of total leaf-surface area and total ground area shaded by the tree:

$$LAI_T = \frac{LA}{GA_T} \quad (3.3)$$

where LA is leaf area per tree (m^2) and GA_T is ground area covered by the tree canopy (m^2).

Since the amount of light transmitted through a canopy is given by (3.2), the amount of light absorbed by the canopy (T) is given by:

$$T = 1 - e^{(-K LAI_T)} \quad (3.4)$$

3.3.2 Photosynthesis of an apple tree canopy

Daily canopy photosynthesis ($g\ CO_2\ m^{-2}\ day^{-1}$) is given by the following equation from Lakso and Johnson (1990) and Charles-Edwards (1982):

$$P_d = \frac{\alpha S h P_{max} \left[1 - e^{(-K LAI_T)} \right]}{\alpha K S + h P_{max}} \quad (3.5)$$

where α is a constant that measures efficiency of leaf photosynthesis ($\mu g\ CO_2\ Joule^{-1}$), S is daily integral of total radiation on a horizontal surface ($MJ\ m^{-2}\ day^{-1}$), h is daylength (seconds) and P_{max} is rate of light-saturated leaf photosynthesis ($g\ CO_2\ m^{-2}\ s^{-1}$). Estimation of daily radiation and daylength are derived from sine functions detailed later in this chapter.

Daily canopy photosynthesis is modified by the effects of temperature, according to the following normalised equation from Lakso and Johnson (1990), where the effect of temperature is included as a fractional reduction of P_d , P_{frac} :

$$P_{frac} = -0.026 + 0.0436\bar{T} + 0.00094\bar{T}^2 - 0.000043\bar{T}^3 \quad (3.6)$$

where \bar{T} is average daily temperature ($^{\circ}C$).

3.3.3 Respiration

Respiration rates of apple trees are low when trees are dormant, rise rapidly during spring, reach a maximum as leaves emerge from their buds and then decline steadily through the remainder of the growing season (Butler and Landsberg, 1981). Research on respiration rates of apple trees and their component parts has shown that respiration increases exponentially with temperature (Proctor et al., 1976; Watson and Landsberg, 1979; Watson et al., 1978; Butler and Landsberg, 1981). Daily respiration of each tree component (R_{d_j}) is therefore expressed as:

$$R_{d_j} = \alpha_j \exp(\beta_j \bar{T}) \quad \text{for } j = L, W, F, R \quad (3.7)$$

where α_j and β_j are parameters. Respiration rates for wood, fruit and roots are measured on a dry weight basis ($g DM gDM^{-1} day^{-1}$) while leaf respiration rates are measured on a surface area basis ($g CO_2 m^{-2} day^{-1}$).

Leaf respiration rates are highest when leaves are young and decrease steadily with age (Watson and Landsberg 1979; Butler and Landsberg, 1981). Respiration rates of the wood are low during dormancy, reaching a maximum at full bloom and declining to pre-bloom levels for the remainder of the season (Butler and Landsberg, 1981). Fruit respiration rates mirror changes in wood respiration rates. During the cell division stage of fruit growth following bloom, Jones (1981) recorded high rates of fruit respiration, which dropped to very low levels one month after cell division commenced. Fruit respiration rates measured in the pre-bloom period by Proctor et al. (1976) were small relative to respiration rates of other tree parts. These authors, however, did not report seasonal changes in root respiration.

Butler and Landsberg (1981) found that the value of β_j remained constant throughout the year for each tree part, but the value of α_j varied. Values of α for leaf, wood and roots were obtained from Elfving et al. (1983) and are listed in Table 3.1.

3.3.4 Environmental parameters

The daily radiation and daylength integrals can be approximated by a sine function with respect to the time of year. Charles-Edwards (1982) uses the following relationships to predict approximate values of each environmental parameter for various locations at any time of the year:

$$X = X_M + X_D \sin \left[\frac{2\pi(t+Z)}{365} \right] \quad (3.8)$$

where X represents either radiation, S , or daylength, h . The sub-scripts M and D represent annual mean value and range respectively, t is date and Z is the date at which the autumn equinox occurs. Date is measured in days from 1 January, thus Z has a value of 283 days in the Northern Hemisphere and 101 days in the Southern Hemisphere. Approximations for S_M , S_D , and h_D are derived from the following relationships (Charles-Edwards, 1982):

$$S_M = 24.3 - 0.264N \quad 10 < N < 55 \quad (3.9)$$

$$S_D = S_M(0.0186N - 0.12) \quad 10 < N < 55 \quad (3.10)$$

$$h_d = \exp(7.42 + 0.045N) \quad 10 < N < 55 \quad (3.11)$$

where N is the latitude. The annual mean value of daylength (h_M) has a value of 4.36×10^4 seconds.

Average daily air temperature (\bar{T}) for a given location as a function of date can also be described by a sine function (Charles-Edwards, 1982):

$$\bar{T} = \bar{T}_M + \bar{T}_D \sin \left[\frac{2\pi \left(t + Z + \frac{N}{2} \right)}{365} \right] \quad (3.12)$$

where \bar{T}_M is mean annual temperature and \bar{T}_D is seasonal variation in amplitude, estimated using the following equations for different locations:

$$\bar{T}_M = 32.5 + 0.45N \quad 10 < N < 55 \quad (3.13)$$

$$\bar{T}_D = \bar{T}_M(0.015N + 0.10) \quad 10 < N < 55 \quad (3.14)$$

3.4 Partitioning

The increase in crop dry weight is divided amongst each plant part in a process known as partitioning. Partitioning occurs on a priority basis. Dry matter also accumulates in the tree as stored reserves. These are used during dormancy and to meet new growth requirements in spring, in the absence of photosynthesis.

3.4.1 Accumulation and use of reserves

The production, partitioning and use of carbon in apple trees follow specific seasonal patterns according to tree activity (Oliveira and Priestley, 1988). When photosynthesis is zero or at a low level during winter and early spring, the perennial parts of the tree (wood and root) are maintained by stored carbohydrate reserves that accumulated within the tree during the previous growing season. Carbohydrates constitute approximately 75 per cent of dry weight of woody plants such as apple trees (Kozlowski and Pallardy, 1997), with a fraction of this being made available as reserves for future use.

Priestley (1970) found that approximately one third of dry matter was extractable as reserves in young apple trees, with as much as one third of this amount being used in early spring growth (Priestley, 1962). Hansen (1977) found that early spring growth may consume four to five per cent of total tree dry weight.

Reserves decline during early spring growth and reach a minimum around bloom (Corelli-Grappadelli et al., 1994). They are replenished over the remainder of the growing season when leaf area is sufficient to sustain growth through photosynthesis (Brown et al., 1985). While both the stem and root contain reserves, reserves tend to be in much higher concentration in the root (Priestley, 1963). The use of stored reserves for growth during spring is modelled as follows:

$$CHO = \zeta \left(R_{t=1} + W_{t=1} \right) \quad (3.15)$$

where ζ is a coefficient denoting release of reserve carbohydrates from the root into the tree and $R_{t=1}$ and $W_{t=1}$ represents root and wood mass at the beginning of the current year's spring growth. If the chilling requirement has not been satisfied, or full bloom has been reached, ζ has a value of zero. In the period after the chilling requirement is satisfied and before full bloom occurs (approximately 8 weeks), ζ is assumed to have a value of 0.05 in accordance with Hansen (1977).

3.4.2 Development of leaf canopy and trunk cross-sectional area

Leaf growth starts approximately two weeks before full bloom (Heim et al., 1979), with leaf area increasing rapidly up to a maximum value. Evidence from Forshey et al. (1983), Porpiglia and Barden (1980) and Ferree (1980) indicates that the foliage canopy of an apple tree is complete three weeks after full bloom. Leaf area becomes stable during midseason and declines in autumn. Leaf senescence occurs over a period of six weeks during autumn following the onset of cooler temperatures and the tree once again enters a period of rest. In the model, commencement of leaf fall is triggered on a particular day, reflecting location of the tree.

Seasonal changes in leaf canopy are implemented by defining triggers activated by temperature. Growth of leaf mass commences when a particular number of hours above a certain temperature, Growing Degree Hours (*GDH*), have accumulated following dormancy release. The value of *GDH* necessary to trigger leaf growth during spring is called *GDHG*.

Maximum leaf mass $w_{L \max}$ attainable by the tree is set at a predetermined level reflecting age and shape of the tree. The values for $w_{L \max}$ over the lifetime of an apple tree are assumed to follow the same pattern of growth as the trunk of the tree, measured as trunk cross-sectional area (*TCSA*) (Westwood and Roberts, 1970; McArtney et al., 1996).

The growth in *TCSA* over time is related, amongst other factors, to rootstock vigour. A large number of rootstocks exist, from those classed as most dwarfing to those classed as most vigorous. In addition to the influence of rootstock vigour, *TCSA* growth is also affected by tree spacing, cultivar, tree management and many factors related to location. The influence of tree spacing, cultivar, tree management and location factors interacting with the effect of rootstock suggest each system possesses a unique pattern of *TCSA* growth that is determined by factors including and in addition to rootstock. Time series data on *TCSA* growth for every apple orchard system is not available and, indeed, rarely reported for any system replicated in experiments.

Long-term time-series data on *TCSA* were, however, available for several systems in a close plant trial, known as *Trial A*, in South Eastern Queensland, Australia (Middleton, 1984; Middleton, unpublished data), and were used to determine general *TCSA* growth patterns over time. Two cultivars were used in *Trial A*: Granny Smith and Delicious. These were planted on three rootstocks: MM.106; M.778 and Seedling, at three planting densities: 997; 1425; and 2990 trees per hectare, with two training systems: Palmette and

Delayed Open Centre. Changes in *TCSA* for all systems in the trial were observed to follow a Gompertz growth pattern over lifetime growth, estimated as:

$$TCSA = TCSA_0 \exp\left[\frac{\mu (1 - \exp(-\delta AGE))}{\delta}\right] \quad (3.16)$$

where $TCSA_0$ is the initial value of *TCSA*, μ is a parameter known as the relative growth rate and δ is an additional parameter describing decay in specific growth rate. Values for μ and δ for Granny Smith growing on MM.106 at a density of 997 trees per hectare are estimated (using equation 3.16) to be 1.00 and 0.22 respectively. These values are assumed to apply to all cultivars grown on MM.106 despite differences caused by cultivar and management practices. Estimation of parameters for additional orchard systems is discussed in Chapter 4.

Once *TCSA* parameters were estimated, data from McArtney et al. (1996) were used to convert growth patterns of *TCSA* into a pattern of growth for leaf area (*LA*) using the following equation:

$$LA_{max,t} = \chi TCSA_t \quad (3.17)$$

where χ is a parameter, estimated from McArtney et al. (1996) to be 0.794. This equation gives the maximum leaf area the tree will obtain in each year of growth. Maximum leaf area is, therefore, predetermined by *TCSA* from equation (3.16), whereas in reality both variables are likely to be influenced by many environmental factors. In its current form, the model only considers annual temperature, radiation and daylength cycles that are known with certainty, thus ignoring stochastic environmental influences.

Leaf area (m^2), and its annual upper bound, maximum leaf area (LA_{max}) are converted to leaf mass w_L , and maximum leaf mass w_{Lmax} ($g DM$) using the following equation from Carbonneau and Lespinasse (1989):

$$w_L = \frac{LA - 95 \times 10^{-6}}{75 \times 10^{-4}} \quad (3.18)$$

Once the w_{Lmax} for a particular age is attained, leaf mass remains constant until leaf fall. Leaf fall is triggered at a particular date, (D_{LF}), based on location. In all simulations, the value of D_{LF} is 130, equivalent to May 10.

3.4.3 Dry matter partitioning

The energy for growth produced as a result of photosynthesis, in the form of dry matter, is allocated to fruit, leaves, wood and root components of an apple tree. This allocation process is known as partitioning, and is affected by whether or not a tree is producing fruit. One noticeable effect of the presence of fruit is a reduction in dry matter partitioned to root and hence a reduction in tree growth (Heim et al., 1979). A heavy fruit load (F_L), defined as fruit number per m^2 leaf area, reduces photosynthesis through a reduction in leaf area (shoot growth) when compared with trees having no fruit (Faust, 1989).

Heim et al. (1979) found that levels of partitioning of dry matter to various tree components were caused almost entirely by differences in fruit load. Using data from Heim et al. (1979), the proportion of assimilates partitioned to tree components during a growing season was estimated in the model using the following equations:

$$\rho_j = \theta_j + \frac{\lambda_j F_L}{\tau_j + F_L} \quad \text{for } j = L, W, F \quad (3.19)$$

$$\rho_R = 1 - \rho_L - \rho_W - \rho_F \quad (3.20)$$

where ρ_j is the proportion of dry matter partitioned to the various tree components and λ_j , θ_j and τ_j are constants whose values are presented in Table 3.1.

In addition to the effects of fruit load, partitioning is also influenced by time of season. At full bloom, almost all dry matter is used for leaf growth but in the following weeks leaf growth attracts a falling proportion of dry matter until leaf growth ceases approximately three months after full bloom when no dry matter is allocated to leaf growth. Wood and root receive a small amount of dry matter for growth in the three months after full bloom. Demand for growth from the fruit becomes an increasing priority and three months after full bloom fruit growth will use all the dry matter once respiration demands of tree parts are satisfied.

The pattern of partitioning is important in perennial tree crops such as apples, because the relative dry matter allocations to tree parts in the current year have implications for growth and fruiting potential in following years. At the extreme, a tree may not bear a regular crop every year but instead a heavy crop may be followed by a small crop because of fruit ‘overload’ in a particular year (Monselise and Goldschmidt, 1982). Influencing the partitioning process in an apple tree through the adjustment of fruit quantity may

correct these biennial bearing patterns if a cultivar is prone to them. One important outcome that normally results from lowering fruit load of a tree is improvement in average fruit size. Adjustment of fruit load in this way is known as thinning, a management practice discussed in detail in Chapter 4.

3.5 Fruit Growth

Once an apple tree reaches bearing age it goes through several stages in the fruit production process: formation of flower buds during the previous growing season; adequate chilling of these fruit buds in winter; flowering, pollination and fruit-set of the flowers in the spring; fruit maturation, ripening and finally harvest during summer and autumn. Temperature plays an important role in the reproductive process.

3.5.1 Dormancy release and heat requirements for bloom

During late autumn, deciduous fruit trees enter a dormant period when buds must be subjected to low temperatures for a certain period if fruit growth and development are to occur in the spring. Release from dormancy occurs once the 'chilling requirement' of the tree has been satisfied. The chilling requirement is normally described in terms of chill units. A chill unit (*CU*) is defined as an exposure to the optimal chilling temperature for one hour, with temperatures above or below the optimum contributing less to chilling time (Table 3.2). A model for determining rest completion for 'Delicious' apples was developed by Shaltout and Unrath (1983), using 7.2°C as the optimum chilling temperature. The range of temperatures and corresponding chill unit values devised by Shaltout and Unrath (1983) are reported in Table 3.2. The following equation was estimated from data in Table 3.2 and is used to estimate chill unit accumulation, *CU*, in the current model:

$$CU = \begin{cases} 0 & \text{if } TH \leq -1.1 \\ a_0 + a_1 TH + a_2 (TH)^2 & \text{if } TH > -1.1 \end{cases} \quad (3.21)$$

where a_0 , a_1 and a_2 are parameters (see Table 3.1), and *TH* is the hourly temperature.

The chilling requirement to break dormancy varies between apple tree cultivars, with most genotypes requiring between 800 and 1200 chill units (Hauagge and Cummins, 1991).

Table 3.2: Corresponding temperature and chill unit value from Shaltout and Unrath (1983)

Temperature (°C)	Chill Unit contribution
-1.1	0.0
1.6	0.5
7.2	1.0
13.0	0.5
16.5	0.0
19.0	-0.5
20.7	-1.0
22.1	-1.5
23.3	-2.0

Shaltout and Unrath (1983) estimate that approximately 1200 chill units are required to break rest of buds on Delicious apple trees and its subclones at an optimal chilling temperature of 7.2°C.

Chill units begin to accumulate in autumn when between 80 and 95 per cent of the leaves have fallen from the tree (Hauagge and Cummins, 1991). Once accumulation starts, the date of dormancy release can be determined from hourly temperature data. Hourly temperatures for a given location and the corresponding contribution of each temperature to chilling time are used to calculate daily chill units. To avoid repeated calculation of this variable, daily chill unit totals enter the model as a vector of numbers.

Once the chilling requirement has been satisfied, the rate of subsequent bud growth is also a function of temperature. Despite the return of warm weather in spring, immediate bud break would put flowers at risk of frost damage. To avoid frost damage, an extended period of favourable weather is required to trigger bud break. The heat requirement of a given cultivar is determined genetically (Faust, 1989), and once this is satisfied, buds will grow at both cool and warm temperatures. The heat requirement to trigger bud break and growth is generally expressed in growing degree hours (*GDH*) and this concept has been used to develop models to calculate full bloom for various deciduous fruit trees (Anderson et al., 1986; Shaltout and Unrath, 1983). The *GDH* model from Shaltout and Unrath (1983) is used to predict date of full bloom using hourly temperature, and is described as:

$$GDH = \sum_{n=1}^{12} (TH - TB)2 \quad (3.22)$$

where TB is the base temperature. The GDH requirement for full bloom of ‘Starkrimson Delicious’ apples, also known as ‘Red Delicious’ or Delicious, is estimated to be 7082 (Shaltout and Unrath, 1983).

An exhaustive list of GDH requirements of each apple cultivar was not found in the literature. Gianfagna and Mehlenbacher (1985) suggest, however, that heat requirements for each cultivar to reach bloom are directly related to bloom date, with chilling requirement playing an insignificant role in its determination. Rather than using the bloom-heat requirement relationship to determine the GDH for each cultivar, GDH for the ‘Delicious’ cultivar was determined, and bloom of all other apple cultivars (and therefore GDH requirements) were determined relative to the bloom date of Delicious. These bloom relativities are listed in Table 3.3 and were obtained from Fleming (1996). Four additional varieties are of interest in this study, and all are assumed to bloom at the same time as Red Delicious. The mix of varieties provides adequate pollinator varieties if all varieties are grown together (Table 3.3).

Table 3.3: Bloom, pollination and harvest information assumed in the biophysical model

Cultivar	Mean CU	Bloom date relative to ‘Red Delicious’	Pollen source	Harvest date relative to ‘Red Delicious’
Granny Smith		Same	Gala, Red Delicious	+ 25 days
Gala		Same	Fuji, Red Delicious	- 25 days
Fuji		Same	Granny Smith, Red Delicious	+ 30 days
Red Delicious	1200		Granny Smith,	0 days
Pink Lady		Same	Granny Smith, Fuji, Red Delicious	+ 54 days

Following bloom, and assuming adequate pollination and fertilisation, there will be a heavy shedding of undeveloped fruitlets, and two to three more waves of shedding after which the final fruit set will be established. In apples, between two and eight per cent of blossoms will set fruit (Westwood, 1993). Fruit set is a term used to describe development of the flower into a fruit following fertilisation.

The processes that lead to final fruit set are not modelled in this study. Rather than model fruit growth as increases in size of a known number of fruit, it is modelled as an increase in total fruit mass. The actual number of apples that make up fruit mass is determined according to fruit load and amount of thinning that occurs.

3.5.2 Fruit growth and harvest

Following initial fruit set, growth and development of the fruit occurs through cell division and cell enlargement. During the first four to five weeks after full bloom, cell division dominates growth. Cell expansion is the most important factor in apple fruit enlargement for the remainder of the season (Faust, 1989). While the fruit growth pattern has usually been described as sigmoidal (Faust, 1989), others have suggested a curvilinear growth phase followed by a linear growth phase (Blanpied, 1966) or an exponential growth phase followed by a linear growth phase (Lakso et al., 1995).

In commercial apple orchards, apple trees are deblossomed and thus prevented from bearing fruit until the tree achieves sufficient vigour. In the model, this is governed by the growth in trunk cross-sectional area. For varieties growing on M.9 and M.26 rootstocks, trunk cross-sectional area must be at least 7.9 cm², and for varieties growing on MM.104, MM.106 and Northern Spy rootstocks, trunk cross-sectional area must be at least 12.4 cm².

Fruit ripening dates vary substantially between apple cultivars, ranging from 70 to 90 days after full bloom (*DAFB*) for early varieties to between 200 and 250 *DAFB* for late varieties. If apples are put in cold storage following harvest they should be picked before they are fully 'eating ripe', otherwise they will be prone to various types of physiological disorders and loss (Westwood, 1993). Fruit harvest is triggered in the model by the achievement of a cultivar specific number of growing degree hours. The appropriate value of growing degree hours is given by *HGDH* and is location specific. The harvest date for Red Delicious is assumed to be 6 March. The harvest dates for the other four varieties considered in this study are listed in Table 3.3.

Potential fruit yield (kg) varies mainly according to the age (size) of the tree. Total fruit yield per tree is initially calculated in the model in terms of grams of dry matter and is converted to fresh fruit weight (*FW*) according to:

$$Y_F = \sigma w_F \quad (3.23)$$

where Y_F is the yield measured in grams of *FW* and σ is the conversion factor between grams of *DM* and grams of *FW*.

3.5.3 Fruit size

While yield per tree (kg) increases nonlinearly as fruit load increases, average fruit weight decreases (Heim et al., 1979). This negative relationship between fruit load and average fruit weight is important to orchard profitability and is the main reason why orchard managers modify fruit load through thinning.

An additional reason for thinning is to modify the biennial pattern of cropping that is common to many apple varieties. Biennial bearing is said to occur when a large crop (number) of fruit is followed by a light crop of fruit. This bearing pattern may also be triggered by certain climatic events such as an unseasonal frost or pest outbreak. Details on how size is determined in the model are given in Chapter 4 where thinning is discussed.

3.5.4 Fruit colour

Apple quality is measured by characteristics such as size, colour, shape, flavour and texture. Fruit quality characteristics result primarily from the scion cultivar and can only be modified, rather than radically changed, by factors related to fruit load and canopy management (Castle, 1995). While all quality factors are important in determining financial returns to growers, only colour and size are considered in the model.

As apples mature, they take on the colours characteristic of the cultivar. While the formation of the colour causing pigment is genetically determined, exposure to light is known to be a crucial factor in red (Saure, 1990) and green colour development (Hirst, Tustin and Warrington, 1990). The formation of red colouring pigment is light dependent, with even slight shading markedly affecting pigment formation (Saure, 1990).

Tree-canopy shape influences the depth and adequacy of light penetration and therefore the level of shading in an apple-tree canopy. Investigation of the relationship between shading and fruit colour suggests that the best colour is obtained with fruit exposure to more than 70 per cent of full sunlight (Faust, 1989). Adequate colour is obtained with 40 to 70 per cent of full sunlight and inadequate colour with exposure of less than 40 per cent (Heinicke, 1963), although 30 per cent is also used as the lower limit for fruit production that has adequate colour (Jackson, 1980b). A canopy shape that is pruned and trained to result in an open tree which allows good transmission of light throughout the whole canopy should therefore allow for good colour development of all fruit.

Jackson (1980b) developed an equation that allows the determination of the leaf area index (LAI) in zones of the canopy receiving adequate light. If adequate light exposure is defined as $uplim$, the LAI in the canopy receiving adequate levels of light is described by L_{uplim} :

$$L_{uplim} = \left[\frac{\ln uplim}{-K} \right] (1 - T_f) \quad 0 \leq uplim \leq 1 \quad (3.24)$$

where $(1 - T_f)$ is equal to the maximum amount of light which can be intercepted by an orchard and K , again is the light extinction coefficient.

Different orchard locations may receive higher or lower levels of above-canopy radiation, and this will lead to different LAI values for 'adequate' light exposure in (3.24). The example following is from Jackson (1997). Suppose location 1 has a lower light intensity than location 2. If 30 per cent light exposure is considered necessary for adequate bud development at location 1, then this level of exposure will be reached at location 2 with a lower level of light exposure, say 18 per cent. Using (3.24), and assuming $K = 0.6$ and $T_f = 0.3$, the LAI receiving adequate light exposure at location 1 will be 1.4 and at location 2 it will be two.

It is assumed that 30 per cent light exposure is necessary for adequate bud development and colour for the particular orchard location used in the model. The value of $L_{0.3}$ is used in the model as the LAI that results in all fruit having adequate colour. Thus, rather than considering all fruit produced, the model thus considers only fruit having adequate colour.

3.6 The Apple Orchard

A typical apple orchard does not form a continuous canopy, rather it consists of either trees grown with access to each from all sides (meadow orchard), or as hedgerows of trees that are contiguous along the row with adjacent hedgerows separated by alleyways to allow machinery access. A wide variety of orchard systems exist, each resulting in different levels of light interception.

3.6.1 Orchard light interception and photosynthesis

When an individual apple tree is considered as part of an orchard, equation (3.5) no longer describes light interception adequately. When light falls on an orchard, some light reaches the orchard floor without passing through the canopy, and shading within rows

also occurs. Mathematical description of light penetration into orchard canopies has proven difficult, however Jackson (1980b) provides a simple, theoretical approach that can be used to predict the maximum light that can be intercepted by a particular orchard system. Jackson (1980b) and Jackson and Palmer (1979) modelled light interception of apple trees in an orchard by considering light transmission (T_L) through discontinuous canopies as consisting of two separate and additive components:

$$T_L = T_f + T_c \quad (3.25)$$

where T_f is light that has passed between the trees and would reach the ground even if the trees were 'solid', and T_c is light which passes through the tree canopy. The value of T_f depends on orchard design (density, tree size and form), and T_c depends upon leaf area and density within the canopy. The value of $(1 - T_f)$ is thus the maximum fraction of available light that can be intercepted by an orchard of given tree dimensions and spacing. Equation (3.4) is redefined in terms of light interception of an orchard (Jackson, 1980b):

$$F_{LT} = F_{max} + F_{max} e^{(-K LAI')} \quad (3.26)$$

where F_{LT} is the fraction of available light that is intercepted by an orchard, and F_{max} is the maximum fraction of the available light which can be intercepted by an orchard of given tree dimensions and spacing:

$$F_{max} = 1 - T_f \quad (3.27)$$

and LAI' is the leaf area per unit of potentially shaded orchard surface area (effective LAI):

$$LAI' = \frac{LAI_T}{F_{max}} \quad (3.28)$$

When considered in terms of an orchard, leaf area index is defined as the ratio between total leaf surface area and the total ground area assigned to trees, including machinery alleyways. The measure of leaf area index for an individual apple tree ignores the contribution of alleyways to total ground area, so values of LAI_T (tree) for a particular planting are higher than the corresponding orchard leaf area index (LAI') (Middleton, 1990).

Redefining light interception using equation (3.26) implies a changed photosynthesis equation:

$$P_d = \frac{\alpha S h P_{\max} \left[F_{\max} - F_{\max} e^{(-K LAI')} \right]}{\alpha K S + h P_{\max}} \quad (3.29)$$

Equation (3.29) rather than equation (3.5) becomes the appropriate daily photosynthesis equation.

4. Management Choices and Practices

In the planting and management of an orchard of apple trees a large number of choices and decisions concerning the most appropriate system face the grower. Barritt (1987) defines an orchard system as the integration of all the horticultural factors involved in establishing and maintaining a planting of fruit trees. Many decisions must be made before planting occurs, including choice of tree density, rootstock (tree size) and pruning and training (tree form).

An important objective of orchard production is to fill the orchard space with productive trees as quickly as possible. Once this is achieved, the objective becomes production of large amounts of high quality fruit. The former objective is attained by encouraging vegetative growth while the latter objective is attained through the restriction of vegetative growth. Vegetative vigour is inversely related to 'fruitfulness' and the balance of the two will determine orchard productivity and fruit quality (Jerie et al., 1989).

Horticultural techniques used to manage vegetative growth and fruit production are pruning, training and thinning. While the level of thinning is determined each year, pruning and training are usually predetermined by choice of density, rootstock and cultivar when the orchard is established. These latter choices are made at planting and assumed to remain unchanged during the life of the orchard.

4.1 Cultivar

The apple cultivar determines fruit variety and fruit features such as size, shape, colour, flavour, firmness, ripening season and pest and disease resistance. The age at which an apple tree first bears fruit (its precocity) will vary according to the rootstock/cultivar combination.

A range of apple cultivars are grown in commercial apple orchards. A variety of reasons exist for choosing a particular cultivar: each type of apple may face distinct market situations and may potentially receive different prices; sequential harvest dates allow for more efficient picking and packing operations; some cultivars have a greater susceptibility to pests and diseases than others; and different cultivars may be necessary for pollination. The biophysical model may be adapted to reflect a diverse range of cultivars by altering the bloom and harvest dates (length of growing season). Cultivars of

interest in model applications of later chapters are 'Hi-Early Red Delicious' (also known as Red Delicious), 'Royal Gala', 'Fuji', 'Pink Lady' and 'Granny Smith'.

4.2 Tree Density

The ultimate size of the tree at maturity determines planting density and is directly related to the rootstock used. The use of dwarfing rootstocks allows trees to be planted closely together in what are known as high-density plantings. The number of trees planted per hectare has implications for the initial investment in trees, input use and per-hectare yield of trees.

Low-density plantings (300 trees per hectare) do not use dwarfing rootstocks and maintenance labour for training is minimal. Returns per hectare are lower because yield per hectare is lower and trees may take up to twenty years to reach maximum production. Pruning and training are much more important tasks for medium-intensity plantings (1000 trees per hectare). Dwarfing rootstocks are normally used in these systems and commercial yields are achieved sooner than with low-density plantings.

In high-density plantings (1500-2000 trees per hectare) and very intense density planting systems (2000-4500 trees per hectare), the cultivar and rootstock choice are critical for size control. In these systems 'very dwarfing' and dwarfing rootstocks are used and trees are planted very close together. Skilled management is required for training and pruning, and a good understanding of tree growth and nutrition is essential.

While initial investment in trees and support structures is higher in High Density Plantings (HDP), a much higher yield is experienced in the early years of orchard operation compared to medium- and low-density planting systems. Yields of dwarf trees at maturity are, however, usually less than those from larger trees on intermediate or vigorous rootstocks. Closer planting of dwarf trees and their earlier bearing habits usually more than compensate for this loss in yield per tree.

Tree density and arrangement is an integral part of orchard profitability. Good orchard design is considered to occur when light intercepted by the trees is maximised, or conversely, light wastage is minimised. When considering designing orchards to minimise light wastage, previous authors have worked in terms of light transmission and the value of T_f for different orchard systems. This parameter describes the amount of light that passes between trees to the orchard floor in the work of Jackson and Palmer (1979). The value of T_f is determined by tree height, shape, spacing and age, row orientation, and by

the angular distribution of direct and diffuse light (Jackson and Palmer, 1979). Many estimates of T_f for different orchard systems are available in the literature (Jackson and Palmer, 1979; Palmer, 1980; Middleton, 1997). Where estimates are not available, computation of T_f can be approximated by the trigonometric relationships between cast shadow length, solar altitude and the diffuse and direct light interception (Jackson and Palmer, 1979). Rather than undertaking this complex calculation of T_f , its value was derived directly from raw data provided by Middleton (1999). The data consisted of measurements of light reaching the orchard floor (T_f) at various times of the day for various orchard systems. The light measurements were made using a flat-bed solarimeter. Where data were not available, estimates were provided by Middleton (S. G., pers. comm.). Since little published data is available on how light interception changes as an apple tree grows, the value of T_f used in the model in most cases is that which would be achieved at maturity.

Tree density and arrangement are both captured through choice of T_f . Because this parameter captures the effects of tree form, it also accounts for the effect of pruning and training on light interception, so, in a sense, it is a proxy for the orchard system, describing tree form and arrangement in the orchard.

4.3 Tree Size (Rootstock Choice)

Tree size is central to an orchard system because of its economic implications. Trees that are large at maturity result in increased labour costs and often take many years to bear fruit. An objective of modern orchard design is to maintain smaller trees that are planted closer together. These smaller trees have the additional advantage of earlier bearing habits. Tree size is most often controlled physiologically through rootstock selection.

In the biophysical model developed in Chapter 3, tree growth is reflected as growth in *TCSA* over time. Rootstock vigour is a significant influence on *TCSA* growth. A large number of rootstocks exist, from those classed as most dwarfing to those classed as most vigorous. A comparison of final tree sizes achieved by cultivars planted on various rootstocks is described in Figure 4.1 (Somerville, 1996).

Cultivars planted on Seedling rootstock could be expected to have the largest trunk cross-sectional area, *TCSA*, at maturity, while those planted on the very dwarfing M.27 rootstock are likely to have the smallest *TCSA* at maturity. Those rootstocks that are of interest in this study are M.9, M.26, MM.104, MM.106 and Northern Spy. The final size

of MM.104 is not shown in Figure 4.1, however its final size is slightly larger than that of M.7 (Somerville, 1996).

In addition to the influence of rootstock vigour, *TCSA* growth is also affected by tree spacing, cultivar, tree management and many factors related to location. An example of location effects is provided by results from identical experiments in several countries as part of the International Apple Growth Study to investigate apple growth responses to climate and the environment. The annual increase in *TCSA* during the first four years of growth of 'Jonagold' apple on M.9 rootstock, grown in seven international fruit-growing regions, varied significantly. At the end of year four, *TCSA* was highest in Italy at approximately 45 cm² and lowest in Washington, USA at approximately 15 cm² (Tustin et al., 1997).

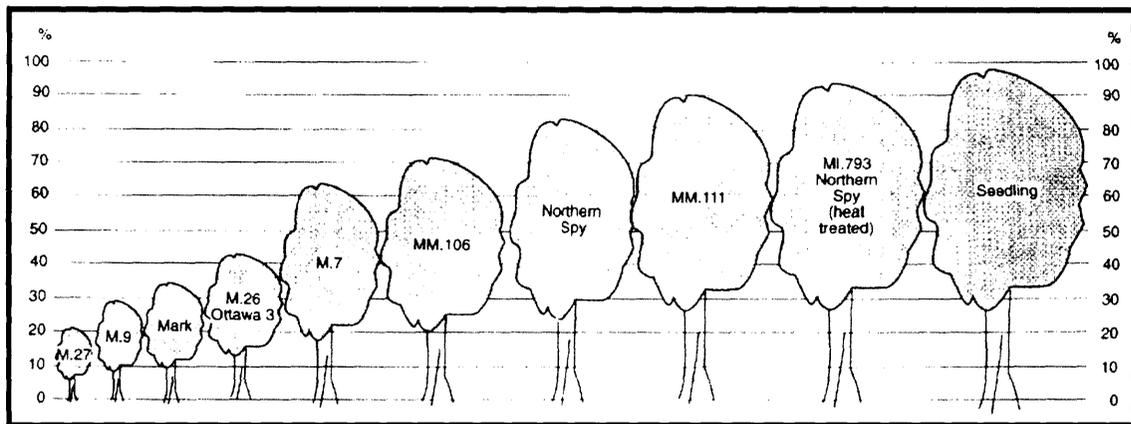


Figure 4.1. Rootstock vigour: the relative vigour of apple rootstocks as compared to apple seedling (100%)

Source: Somerville, 1996, p. 136

Cultivar and spacing may also have an effect on growth in *TCSA*. In Italy, Fuji apples growing on M.9 rootstock at a spacing of 4444 trees per hectare achieved *TCSA* of 6.2, 8.15 and 11.51 cm² during years one, two and three respectively after planting (Costa et al., 1997). This can be compared to changes in *TCSA* for Delicious apples on the more vigorous M.26 rootstock at a slightly reduced density of 4167 trees per hectare of 5.0, 6.13, and 7.71 cm² during years one, two and three following planting.

The influence of tree spacing, cultivar, tree management and location factors interacting with the effect of rootstock suggest each system has a unique pattern of *TCSA* growth. The effect of a particular rootstock on apple tree growth is modelled through changes in parameters contained in the Gompertz equation (3.16), used to model annual growth in *TCSA*. Ideally, time-series data on *TCSA* growth for every system (density, rootstock, cultivar, and location) would be available allowing accurate estimation of the Gompertz

parameters. Such comprehensive time-series data on *TCSA* growth is not available and, indeed, rarely reported.

TCSA growth patterns for cultivars growing on M.9, M.26, MM.104, MM.106 and Northern Spy rootstocks are, nevertheless, necessary for the model applications undertaken in this study. The horticultural literature was searched for experimental data on *TCSA* that could be matched to each system (in this case rootstock and density only) investigated. The value of $TCSA_0$ was assumed to be 1.57 cm² for all rootstocks at planting. This value is taken from experimental data in Tustin et al. (1997) and was the only actual value of $TCSA_0$ located in the literature. Using this value of $TCSA_0$, values of μ and δ for each system were estimated using available data shown in Table 4.1 and Figure 4.2.

Table 4.1 Values of μ and δ used in the calculation of Trunk Cross-Sectional Area for each system under study

Rootstock of system modelled	System Density	Density in source data	No. data points for estimation	Data source	$TCSA_0$	Estimated parameters	
						μ	δ
M.9	4400	4444	3	Costa et al (1997)	1.57	1.87	0.89
M.9	2666	2778	3	Costa et al (1997)	1.57	2.29	0.95
M.26	1666	816	8	Hirst and Ferree (1995)	1.57	1.2	0.29
MM.104 (M.7)	800	816	8	Hirst and Ferree (1995)	1.57	1.32	0.3
MM.106	1000	997	14	Trial A ^a	1.57	1.00	0.22
Northern Spy	280	480	2	Campbell et al. (1996)	1.57	0.98	0.2

^a Middleton (1984; unpublished data).

Data from Costa et al (1997) were used to estimate parameters for two systems growing on the very dwarfing M.9 rootstock. The systems reported by Costa et al. (1997) were well matched in terms of density with the M.9 systems of interest in this study. Using three data points for each system, the parameter values were determined through a purpose-built search algorithm. Experimental data for M.26 at a density of 1666 trees per hectare was not located. Data from Hirst and Ferree (1995) where cultivars were grown on M.26 at the lower density of 816 trees per hectare was the only satisfactory data found. It is likely that actual *TCSA* growth pattern of M.26 at 1666 trees per hectare is less vigorous than the estimates used. Data from Hirst and Ferree (1995) were also used to determine parameter values that might apply to cultivars on MM.104 grown at a density of 800 trees per hectare. In this case, experimental data for cultivars growing on M.7 rootstock were used as a proxy. This rootstock is slightly more dwarfing than MM.104

and hence it is likely that the parameters estimated slightly underestimate actual growth patterns. The only data on *TCSA* for cultivars on Northern Spy rootstock at relatively low densities was found in Campbell et al. (1996). Only two data points were available, when the trees were nine and sixteen years old. The parameters μ and δ for this system were thus determined algebraically.

The *TCSA* patterns as determined by the parameters assumed to hold for each system being investigated are shown graphically in Figure 4.2. The most vigorous rootstock is Northern Spy and the least vigorous is M.9. Cultivars growing on M.9 rootstocks are expected to achieve maximum yield and hence maximum *TCSA* in year four (S.G. Middleton, 1999, pers. comm.), a situation that occurs using the estimated parameters.

While the method used to determine growth in *TCSA* for each system is not entirely satisfactory, it has been adopted due to lack of comprehensive long-term data on trunk growth that specifically matches the density and rootstock of each system under investigation. *TCSA* growth parameters for each system would be more accurate if they were estimated from actual experimental data. Whether these parameter values hold for the same system at locations other than those in the experiments (Table 4.1) is an empirical question that needs to be tested under different environmental and management conditions.

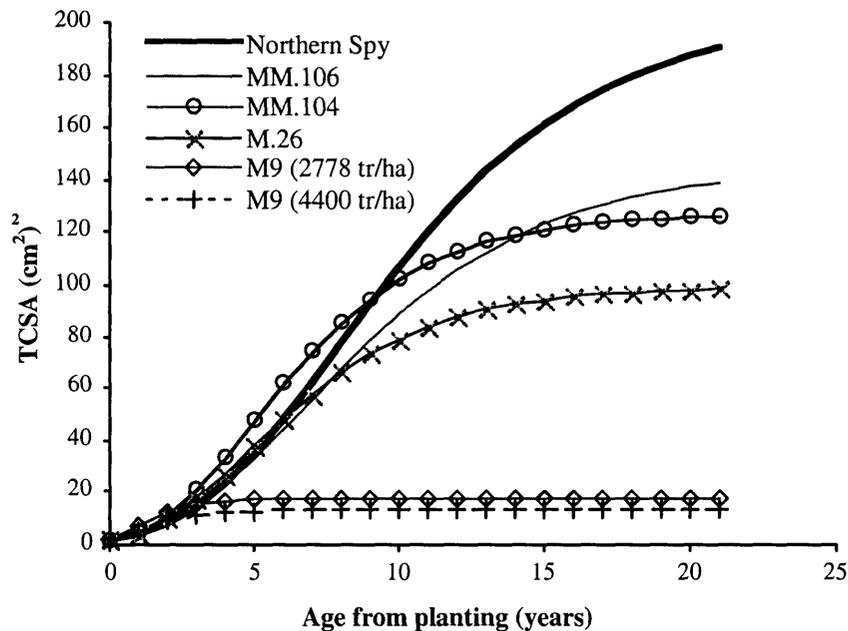


Figure 4.2 Changes in *TCSA* over time for each rootstock considered in this study, assuming the parameter values of Table 4.1

4.4 Pruning and Training

Techniques that control shape, size and direction of tree growth are known as training and removal of particular tree parts is known as pruning. Pruning of an apple tree occurs throughout its lifetime. In a young tree, pruning is undertaken with the aim of training the tree to produce a certain shape and structurally sound framework that can hold heavy crops, allow easy access to the picker and pruner, allow thorough penetration and tree coverage to orchard sprays and, importantly, produce a shape that allows light to enter all parts of the tree. Light interception thus depends on the tree form that results from pruning and training.

Robinson et al. (1991) summarise two approaches on which most training systems are based. The first is to allow the tree to grow to its natural form which allows light penetration through many small openings in the canopy. Examples include the multiple leader, central leader, vertical axis, or slender spindle tree forms. The second approach is to restrict tree canopies to certain geometric forms with fewer large, permanent openings that allow light penetration. Examples of this approach include thin restricted single planes of foliage such as narrow hedgerows, tree walls and trees trained to the A, V and T forms. Each method has associated labour costs to maintain branch training and, in the case of restricting trees to geometric forms, the costs of trellising structures are substantial. Appropriate training systems in very high density plantings include trellis, hedgerow, double row and spindle bush systems. For high density plantings central leader pyramid shaped training is essential (Fleming, 1996).

The effect of different pruning and training techniques on tree shape and therefore light interception is also captured by the value T_f . Not all pruning and training techniques are investigated in this study. Rather, the most common methods for each tree size have been chosen.

The V-trellis (Figure 4.3) and slender spindle (Figure 4.4) systems have been chosen for trees on the dwarfing M.9 rootstock, the traditional 'vase' method (Figure 4.5) has been used for cultivars on Northern Spy rootstock planted at low densities and the central leader method (Figure 4.6) has been chosen for all remaining cultivar/rootstock combinations.

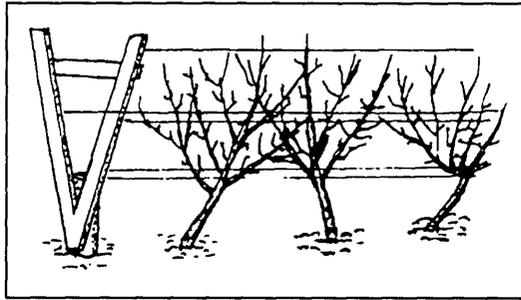


Figure 4.3: V-trellis

Source: Hampson et al. (1998) (p.75).

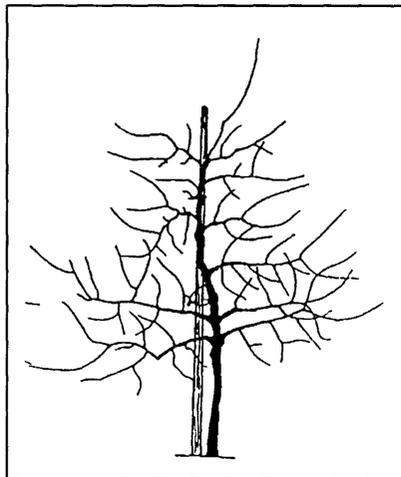


Figure 4.4: Slender spindle

Source: Mika (1992) (p.34).

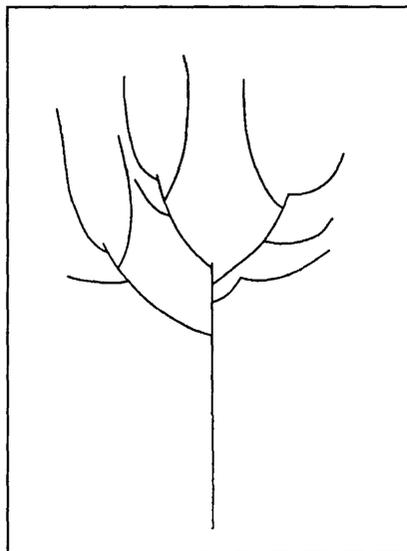


Figure 4.5: Vase shape

Source: Somerville (1996) (p.87).

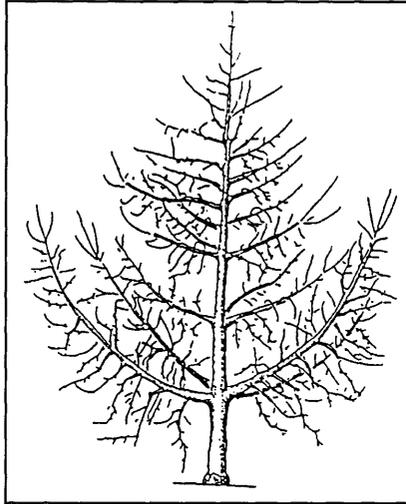


Figure 4.6: Central leader

Source: Kikuchi et al. (1997) (p.542).

4.5 Thinning

Under optimal conditions, an apple tree will set more fruit than can be supported by the tree to grow to a commercially desirable size. If this situation is not rectified it may result in an insufficient number of flower buds in the following year, especially in those varieties that have a tendency to biennial bearing. Additional consequences of too many fruits on a tree are lack of root growth and insufficient accumulation of reserves to allow development of winter hardiness (Faust, 1989). To avoid these problems, an orchardist can influence the fruit load through the management practice known as thinning which involves removal of apple flowers or fruit clusters.

Thinning stimulates cell division and cell expansion of remaining fruits, resulting in an increase in average fruit size (Sharples, 1968). The leaf-to-fruit ratio increases following fruit removal and more nutrients become available to develop the remaining fruit. While the remaining fruits will be larger at harvest, this increase in fruit size is not directly proportional to the increase in the number of leaves per fruit (Westwood, 1993), resulting in some yield reduction. While thinning does reduce total yield, it does not necessarily reduce total marketable yield.

Thinning is undertaken by hand or chemical means or using a combination of both. Chemical thinning involves spraying chemical thinning agents on apple trees to reduce blossom or fruit numbers, using either hand held lances or airblast sprayers. Hand thinning involves removing small and weak fruitlets with some consideration given to the spacing of fruits on the tree and is the method of thinning assumed in this study.

The timing of thinning is thought to be critical for final fruit size at harvest regardless of thinning technique. McArtney et al. (1996) found that the mean increase in fruit weight at harvest of two cultivars was influenced by timing of hand thinning to a much greater extent than by the number of fruit left on the tree – earlier thinning resulted in heavier fruit at harvest. Westwood (1993) explains that if thinning is accomplished before the end of the cell division period it may stimulate production of more cells per fruit. This may then result in larger fruit than if fruit were thinned during the cell enlargement period that follows. The implication is that, if thinning occurs at or soon after full bloom, more fruit could be left on the tree without sacrificing mean fruit size at harvest (McArtney et al., 1996) thus improving marketable yield. In this study, it is assumed that thinning occurs before the end of the cell division period.

From a financial perspective, the effect of thinning on average fruit weight and consequently on the commercial value of yield is important. Following picking, apples are graded and packed into various ‘count’ sizes that are based on individual fruit weight and reflect number of fruit per carton. The value of the apple harvest is closely related to fruit size. Generally a crop of small apples is worth less than the same weight of larger apples, hence the incentive to improve fruit size through thinning.

Assuming that all apple cultivars are prone to biennial bearing, a biennial bearing pattern is imposed on fruit growth that sees a large crop followed by a light crop. Data on natural fruit bearing patterns is scarce although the biennial bearing pattern simulated by the biophysical model does compare reasonably with the fruit mass data from *Trial A* (Middleton, 1984; Middleton, unpublished data). The biennial bearing pattern is simulated as follows:

$$EFL_t = (BFL - (F_{L,t-1} - BFL)) \quad (4.1)$$

where EFL_t is expected fruit load when no thinning takes place, BFL is fruit load that would lead to minimal or no biennial bearing and $F_{L,t-1}$ is fruit load in the previous year. The value of EFL_t depends on the amount by which actual fruit load exceeded BFL in the previous year. It is likely that the value of BFL varies with cultivar, rootstock and tree age, although these effects are ignored in the present study due to lack of experimental data and a single estimate is used. The estimate of BFL is set at a level that appears reasonable to the author given data from *Trial A* (Middleton, 1984; Middleton, unpublished data).

The process of thinning leaves a proportion of the original amount of fruit on the tree. The actual fruit load that results from thinning is calculated as:

$$F_{Lt} = ELF_t \cdot thin_t, \quad 0 \leq thin_t \leq 1 \quad (4.2)$$

Once F_{Lt} is determined, fruit number (FN) is calculated according to:

$$FN_t = F_{Lt} \cdot LA_{max_t} \quad (4.3)$$

where LA_{max_t} is the maximum leaf area, calculated from equation (3.17). Finally, average fruit weight (FW) is calculated as:

$$FW_t = \frac{Y_{Ft}}{FN_t} \quad (4.4)$$

where Y_{Ft} is the yield per tree measured in g FW (equation 3.23). Average fruit weight is used in the economic model to determine the profitability of a given thinning strategy.

4.6 Tree Replacement

Another important management decision choice is the age at which trees are replaced. This decision, along with the appropriate replacement system has received considerable attention in the literature (Faris, 1960; Perrin and Proctor, 1974; Rae, 1977; Khera and Crowe, 1980; Gerling, 1981; Childs, 1982; Bauer et al., 1990; and Goedegebure, 1988). With modern tree varieties, the decision of when to replant the orchard seems to be determined more by consumer demand for new varieties (and hence price) than by decreases in productivity of the orchard over time.

When deciding on the replacement system, such a large number of alternatives is available (rootstock/cultivar/training combinations) that it is impossible to consider all of these. Commonly, authors have chosen a small number of alternatives and found the most profitable replanting system from these. These authors are not finding optimal replacement strategy as such, rather, they are finding one strategy out of a selection of strategies that maximises profits, given a specific set of costs, prices and grower preferences that are known with certainty, eg. Childs et al. (1983).

Techniques used to determine the most profitable of the alternative strategies include comparing the net present value or internal rate of return of each system. Choosing the replacement strategy that gives the maximum average annualised net returns (*AANR*) has also been favoured by some authors (Faris, 1960; and Bauer et al., 1990). Other authors have extended the *AANR* approach, and have set a life span for the replacement orchard and amortised its *NPV* using the annuity factor. The current orchard is replaced if the expected net revenue next year for the current orchard is less than the value of the *AANR* calculated over the lifetime of the replacement orchard. Authors who have used the technique in this way include Perrin and Proctor (1974), Gerling (1981), Khera and Crowe (1980), Rae (1977) and Goedegebure (1988). The timing of replacement is not considered in these modelling approaches. Childs (1982) suggests a dynamic programming approach as a method to solve the problem of when to replace the orchard and develops a model that simultaneously chooses the best among several replacement planting systems.

The bioeconomic model developed here is based on the premise that productivity of trees may be maintained for many decades given proper attention to tree health which, on the basis of the evidence, seems realistic. As such, no effect of ageing on tree productivity has been included in the model. Any such ageing effect would, in any case, be arbitrarily selected.

Given that only a sub-set of possible future replacement alternatives is known with certainty, the methods of selecting the best replacement policy have been adequately covered in the literature. As a result, the questions of optimal timing of replacement and optimal replacement strategy are not considered in this thesis.